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RESEARCH MEMORANDUM

INVESTIGATION OF PERFORMANCE OF SEVERAL DOUBLE-SHROUD EJECTORS AND EFFECT OF VARIABLE-AREA EXHAUST NOZZLE ON SINGLE EJECTOR PERFORMANCE

By C. W. Ellis, D. P. Hollister, and H. D. Wilsted

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

An investigation was made to determine briefly the characteristics of a double-shroud cooling-air ejector. Also, the performance of a single-shroud ejector having a clamshell-type variable-area actuating nozzle was compared with that of an ejector having a conical nozzle.

For the models investigated, the experimental results indicated that the differences in the variable-area and conical nozzle ejector performance are due primarily to flow restrictions in the cooling passage introduced by the clamshell protrusions, rather than the nonplanar and noncircular exit. The investigation of double-shroud-ejector performance, while not completely general in application, does indicate that an ejector of this type could be designed to operate satisfactorily, that is, with a ratio of tertiary to secondary air weight flow of about 0.2. In order to obtain such performance, the difference between the diameter ratios and spacing ratios of the two shrouds should be small.

INTRODUCTION

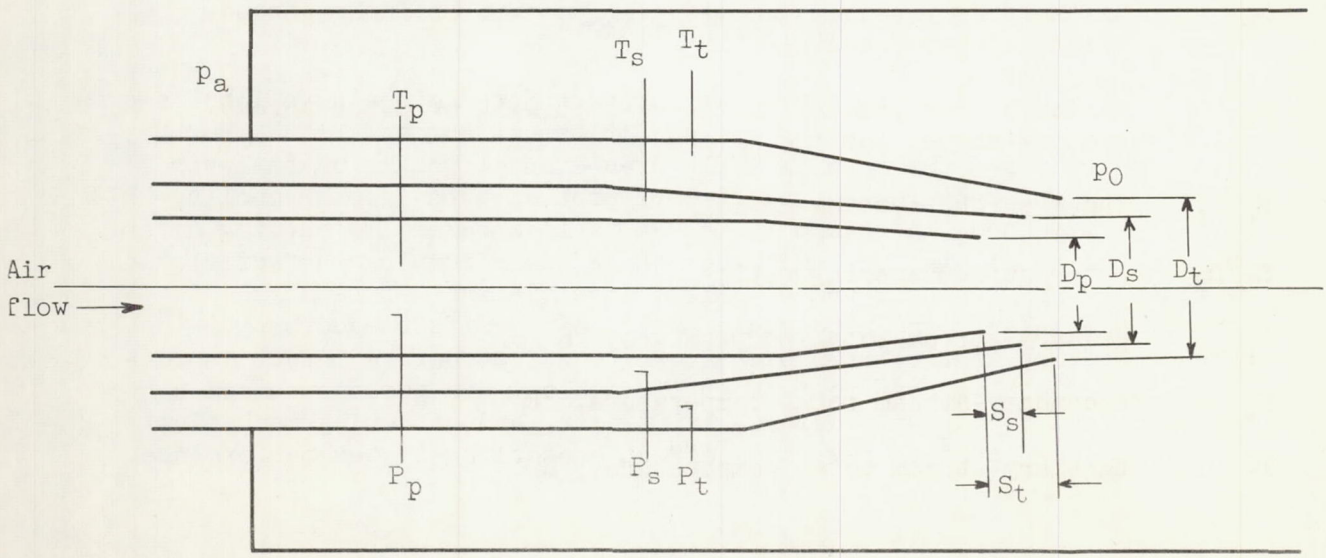
Tail-pipe cooling requirements for turbojet engines have increased markedly with the use of afterburning for thrust augmentation. Furthermore, the required use of a variable-area exhaust nozzle on tail-pipe-burning engines complicates the cooling problem when ejector cooling-air pumps are used. A change in the variable-area nozzle setting alters the ejector configuration, and hence the ejector pumping characteristics, as shown by references 1 and 2. Also, if a clamshell-type nozzle is used, the nonplanar and noncircular outlets may affect ejector pumping characteristics as they have been shown to affect nozzle thrust in reference 3. The flow restrictions in the cooling-air passage caused by variable-area nozzle protrusions, stiffeners, and actuating mechanism may also be expected to have some effect on cooling-system performance.

As an integral part of some engines, a conventional, single-shroud ejector is supplied to cool the engine tail pipe. In some aircraft installations, an additional quantity of air is required for cooling the aircraft structure. It is possible that this additional cooling air can be pumped by the addition of an outer concentric ejector shroud without appreciably affecting the performance of the primary ejector. Because performance and design information are nonexistent for double-shroud-type ejectors, a brief investigation of their performance has been conducted at the NACA Lewis laboratory.

The double-shroud ejector configurations used in the investigations described in this report were designed by an aircraft manufacturer for application to a specific aircraft installation. These configurations incorporated primary nozzles which simulated a clamshell-type variable-area nozzle. Although this investigation was quite limited in the number of configurations investigated, sufficient data were obtained to show trends in double-shroud-ejector performance resulting from variations in length and exit diameter of both inner and outer shrouds. Performance data were obtained for each configuration over a range of primary-air and cooling-air pressure ratios with the variable-area nozzle simulated in both open and closed positions. The performance of a single-shroud ejector having the variable-area nozzle was determined and compared with the same ejector shroud having fixed conical primary nozzles.

SYMBOLS AND NOMENCLATURE

The symbols and ejector nomenclature used in this report are defined with the help of the following schematic sketch of a double-shroud ejector:



D_p	exit diameter of primary nozzle
D_s	exit diameter of inner shroud
D_t	exit diameter of outer shroud
D_s/D_p	inner-shroud diameter ratio
D_t/D_p	outer-shroud diameter ratio
F_j	gross thrust of primary nozzle with shrouds removed, lb
Fe_j	gross ejector thrust, lb
Fe_j/F_j	gross thrust ratio
P_p	primary-stream total pressure, lb/sq in. abs
P_s	secondary-stream total pressure, lb/sq in. abs
P_t	tertiary-stream total pressure, lb/sq in. abs
P_p/p_0	primary pressure ratio
P_s/p_0	secondary pressure ratio
P_t/p_0	tertiary pressure ratio
p_0	ejector-discharge pressure, lb/sq in. abs
p_a	atmospheric pressure, lb/sq in. abs
S_s	distance from primary nozzle exit to exit of inner shroud, inner-shroud spacing
S_t	distance from primary nozzle exit to exit of outer shroud, outer-shroud spacing
S_s/D_p	inner-shroud spacing ratio
S_t/D_p	outer-shroud spacing ratio
T_p	primary-stream total temperature, ^{o}R
T_s	secondary-stream total temperature, ^{o}R
T_t	tertiary-stream total temperature, ^{o}R

W_p primary weight flow, lb/sec

W_s secondary weight flow, lb/sec

W_t tertiary weight flow, lb/sec

W_s/W_p secondary weight flow ratio

W_t/W_p tertiary weight flow ratio

APPARATUS

Ejector Research Facility

The ejector research facility shown in figure 1 consists of concentric ducting simulating an engine tail pipe and a cooling-air passage. The lower portion of the facility swings freely to allow measurement of ejector thrust by means of a calibrated, strain-gage-type thrust meter. The air supplied to the primary nozzle and to the two cooling-air passages is separately measured by A.S.M.E. flat-plate orifices. The primary-air total pressure was measured by a probe projecting about one third of the duct diameter into the stream. Total pressure surveys had shown that measurements at this location gave the average of the total pressure profile. Primary-air temperature was measured by a single, bare-wire, iron-constantan thermocouple projecting about one third of the duct diameter into the stream. Two pressure probes and two thermocouples were also provided in each of the cooling annuli.

The ejector discharged into an exhaust chamber in which the pressure could be reduced to increase the pressure drop across the ejector. The discharge pressure was measured by two static pressure probes at the lip of the outer shroud.

Ejector Models

The nozzles used to simulate a variable-area nozzle in the ejector models are shown in figure 2. The exit of the closed nozzle was elliptical and nonplanar and had a major axis of 3.4 inches and a minor axis of 2.6 inches. The open nozzle had essentially a planar and circular exit with a diameter of 3.66 inches.

The relative location of the shrouds with respect to the variable-area nozzle is shown in figure 3. The inner shroud had a 4.5-inch-diameter exit. The length of this shroud was altered once during the

investigation by cutting a portion off the end, which made the exit diameter 4.65 inches. The outer-shroud position could be varied by inserting spacers between the inlet duct and the shroud. Two outer shrouds were used in this investigation, one having a 5.10-inch-diameter exit and the other a 4.72-inch-diameter exit. In order to determine the effects of the double shroud on ejector performance, the ejector performance was also determined with the outer shroud removed. Two fixed conical primary nozzles were evaluated during this investigation so that their performance could be compared with that of the two variable-area primary nozzles. In order that the exit areas be approximately equal to the corresponding areas of the variable-area nozzles when open and closed, the conical nozzles had exit diameters of 3.66 and 2.90 inches, respectively. The corresponding half-cone angles were 6° 50' and 9° 22'.

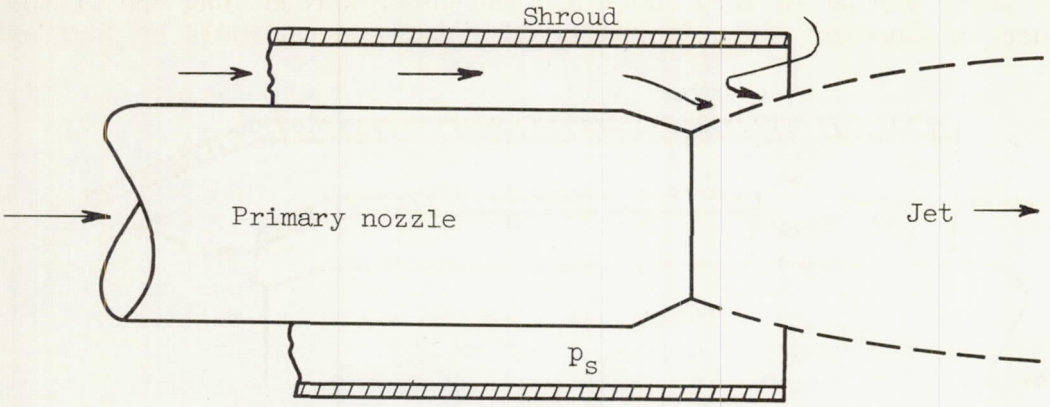
PROCEDURE

The investigation was conducted with atmospheric air compressed to 40 pounds per square inch gage and supplied at 80° F. Although ejector performance was determined with 80° F primary and secondary air and therefore required no temperature correction, the weight flow ratios presented herein are multiplied by $\sqrt{T_s/T_p}$ as a reminder that the application of these flow data to hot jet installations requires a temperature correction. Various primary and cooling-air pressure ratios were obtained by throttling the inlet air and/or reducing the exit pressure in the plenum chamber. The pressures in the two cooling passages were maintained approximately equal to simulate a common inlet and plenum chamber for the two parallel cooling passages. The jet thrust of the ejector was obtained by adding to the strain-gage reading the negative force imposed on the system by the difference between atmospheric pressure and the ejector discharge pressure in the exhaust plenum chamber. This force had previously been determined by calibration.

RESULTS AND DISCUSSION

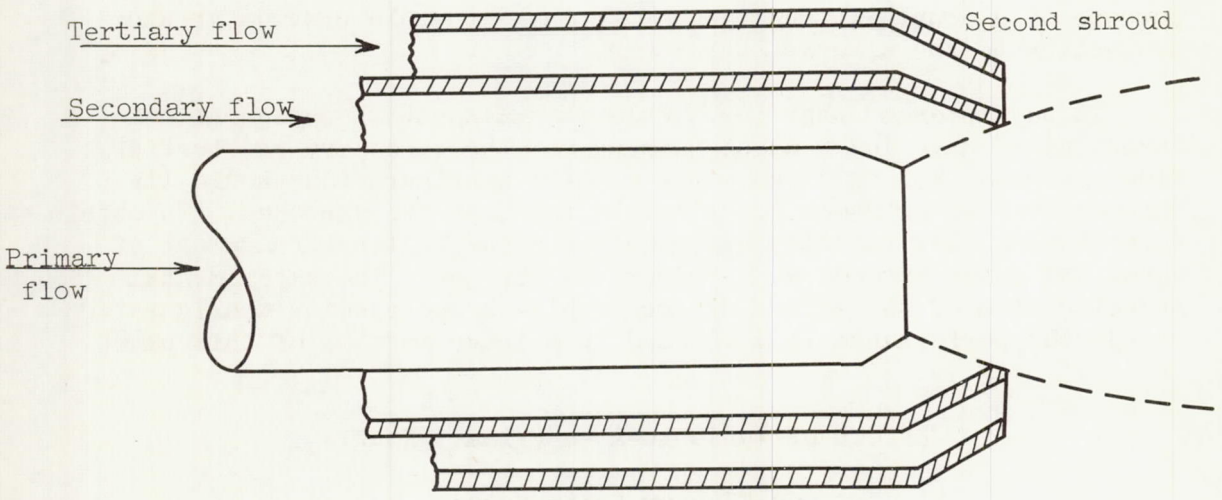
Mechanics of Ejector Flow Systems

A somewhat simplified description of the ejector pumping mechanism is that an ejector induces secondary or cooling-air flow by virtue of the high viscous forces set up at the boundaries of a free jet. If the shroud is placed so as to leave a large gap between itself and the jet boundary as shown in the following sketch, air can be entrained by flow through either the fore or aft portion of the shroud. Restricting the flow at the forward end of the shroud would not appreciably reduce the



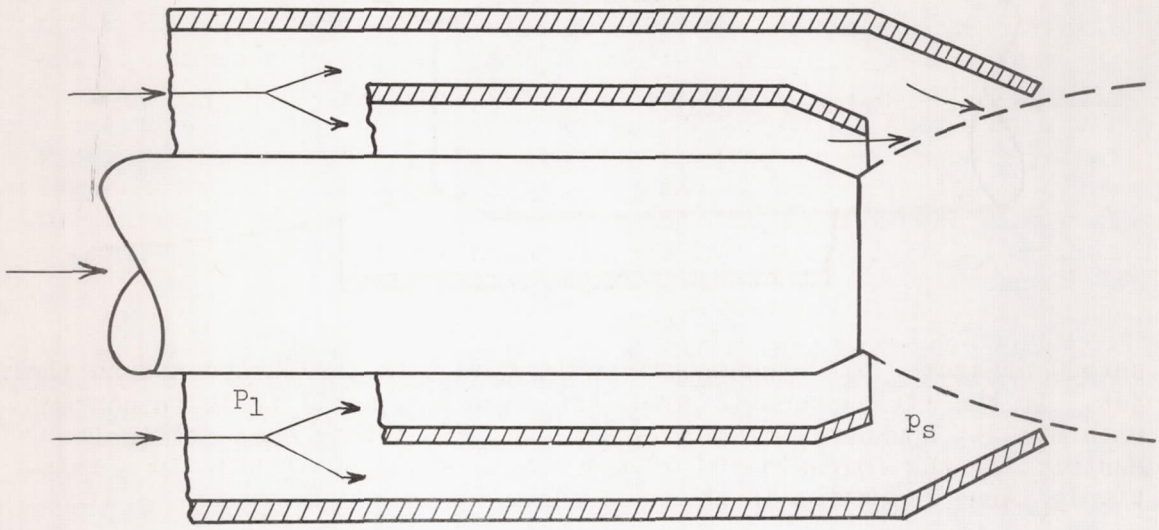
shroud pressure p_s because air would flow into the shroud around the jet. If the mixing tube is moved aft, however, until it is in contact with the jet boundary, flow inward around the jet is made difficult. Restricting the foreward end of the shroud would now result in a relatively large reduction in shroud pressure.

The operational mechanism of the simple ejector applies equally well to the double-shroud ejector. The addition of an outer shroud to an ejector may or may not affect ejector performance, depending on the position of the outer-shroud exit with respect to both the inner-shroud exit and the expanding jet. For example, with coplanar shroud exits, such as shown in the following sketch,



the expanding jet cannot reach the outer shroud and it would be, therefore, quite ineffectual in pumping air through the tertiary flow system.

If the inner shroud is very short and the outer shroud long and if the increase in diameter ratio is small, the inner shroud would be ineffective



as an ejector and the outer shroud would perform as a single ejector. If the air entering the secondary and tertiary flow systems has a common source, such as shown in the preceding sketch, the inner shroud serves only as a splitter with the air flowing through the parallel passages by virtue of the pressure gradient $P_1 - p_s$. The inner shroud may serve as a radiation shield and this configuration would serve, therefore, the purpose of a double-shroud ejector in that it would provide greater protection to the aircraft structure.

It was intended that the double-shroud ejector configurations investigated have independent pumping for the secondary and tertiary flow systems. For this case, the ejector configuration should lie between the two extremes described in the last two sketches. To obtain a particular flow distribution requires a particular arrangement of inner and outer shrouds with respect to the jet. The experimental investigation of the effect of the double-shroud-ejector configuration on ejector performance is discussed in a later portion of this paper.

Effect of Variable-Area Primary Nozzle on Ejector Performance

The ejector configurations under consideration not only incorporated double shrouds but also included a variable-area nozzle. Because

the variable-area nozzle of the eyelid type generally has a nonplanar discharge opening and generally poor exterior configuration for an efficient flow system, it was necessary to determine the magnitude of these factors on ejector performance. In order to simplify the investigation, the magnitude of these effects was determined by comparing the performance of a single-shroud ejector having in turn the variable-area and fixed conical nozzles (fig. 4). Both weight flow ratio and jet thrust were greater with the conical nozzle. Because diameter ratio, spacing ratio, primary pressure ratio, and secondary pressure ratio were duplicated, it was reasoned that the difference in performance must result from (a) the effects of the nonplanar and noncircular exit or (b) restrictions in the secondary passage due to clamshell sections.

The effect of restrictions in the secondary passage was investigated by adding to the conical nozzle a flange to reduce the secondary passage area to that with the clamshell-type nozzle. This flange was simply a brass ring 1/8 inch thick having an inside diameter of 3.75 inches and an outside diameter of approximately 4.80 inches, which was attached to the conical nozzle at a point 1.54 inches from the exit. As shown in figure 5, with equal cooling-air-flow passage areas, weight flow ratio and thrust ratio for the two ejectors were virtually equal. The effects of secondary-flow passage area on performance, as shown in figures 4 and 5, demonstrate that it is not sufficient to specify only the spacing and diameter ratios to insure identical performance unless these configuration parameters insure a unique cooling-air-passage flow area and pressure drop, which will produce equal pressures in the mixing plane. Inasmuch as making the cooling-air-flow passage areas equal practically eliminated the performance differences between the conical and variable-area nozzle ejectors, it is concluded that the noncircular and nonplanar exit of the variable-area nozzle had a negligible effect on ejector performance.

Double-Shroud-Ejector Performance

Pumping characteristics. - The double-shroud ejector configurations incorporated the simulated variable-area nozzle. The protrusions on the variable-area nozzle created restrictions in the cooling-air passage, causing a reduction in ejector performance. The results of the double-shroud ejector investigation are, therefore, applicable only to the particular geometries used. Had the secondary total pressures been measured downstream of the restriction, near the exit plane of the nozzle, the results would have been more generally applicable. Nevertheless, as mentioned previously, the performance trends should be indicative of those to be expected for other double-shroud ejectors.

The pumping characteristics of the double-shroud-ejector configurations with the open primary nozzle are compared with the single-shroud-ejector performance in figure 6. The addition of the outer shroud increased the ratio of secondary to primary weight flow for all configurations investigated except configuration D at a primary pressure ratio of 3.7 (fig. 6(c)), which exhibited a small reduction in secondary weight flow ratio. Increasing the spacing ratio S_t/D_p of the outer shroud increased the secondary air flow ratio at a primary pressure ratio P_p/p_0 of 1.6, but as the pressure ratio was increased to 3.7 the trend was reversed for all but low secondary pressure ratios. The tertiary weight flow ratio, however, increased with increased spacing throughout the range of conditions investigated. A reduction of both outer-shroud diameter ratio and spacing generally reduced both the secondary and tertiary weight flow ratio. Cutting back the inner shroud to give a shorter spacing and larger diameter ratio (configuration F) gave a configuration which was far more sensitive to changes in primary pressure ratio than the other double-shroud-ejector configurations.

The pumping characteristics of configurations with the simulated closed primary nozzle position are shown in figure 7. As would be expected, with the larger diameter ratio configuration the secondary and tertiary weight flow ratios are more sensitive to secondary pressure ratio than the previous configurations but are generally less sensitive to small changes in configuration. At a primary pressure ratio of 1.6, an increase in outer-shroud spacing increased the secondary weight flow ratio but had little effect on tertiary weight flow ratio. At primary pressure ratios of 2.1 and 3.7, the change in the outer-shroud spacing had little effect on the secondary and tertiary weight flow ratios. At the highest primary pressure ratio, 9.4, an increase in outer-shroud spacing generally decreased both the secondary and tertiary weight flow ratios. A reduction in outer-shroud diameter ratio and spacing (configuration DD compared to AA) generally had little effect on the secondary weight flow ratio but greatly reduced the tertiary weight flow ratio. Cutting back the inner shroud to give a larger diameter ratio and shorter spacing (configuration FF) generally had little effect on either the secondary or tertiary weight flow ratios; this indicated that the outer shroud was generally providing the ejector action for these configurations (AA through DD).

The use of tertiary air for aircraft structure cooling generally requires only one-fifth to one-tenth the air required for tail-pipe cooling. For most of the configurations investigated, the tertiary air flow tends to equal or exceed the secondary air flow. Configurations D and DD indicate, however, that by a reduction in the diameter and spacing ratios of the outer shroud, the tertiary weight flow ratio can be satisfactorily controlled.

The operation of an engine with a variable-area nozzle in conjunction with afterburning and nonafterburning results in changes in both cooling requirements and cooling-air ejector performance. At approximately take-off pressure ratios, 1.6 to 2.1, the secondary and tertiary cooling-air flow starts at lower secondary pressure ratios when the jet nozzle is in the open or afterburning position than when it is in the closed or nonafterburning position, as shown by comparison of figures 6(a) and 6(b) with figures 7(a) and 7(b). However, at reasonably high flight speeds (primary pressure ratio of 3.7, and secondary pressure ratios above 1.05), the secondary cooling-air flow would be much greater for the closed primary nozzle or nonafterburning configuration as shown by comparison of figures 6(c) and 7(c). Even when the differences in primary gas temperatures between afterburning and nonafterburning conditions are taken into account, the cooling-air flow ratio would generally be greater with the primary nozzle in the closed position. At higher primary pressure ratios this condition should be even more pronounced. The tertiary weight flow ratio, however, may be either larger or smaller when the primary nozzle is in the closed position, depending on the configuration used.

Thrust of double-shroud ejector. - The ratio of ejector gross thrust to conical-nozzle (ejector shrouds removed) gross thrust Fe_j/F_j is shown in figure 8 for the open-primary-nozzle configurations and in figure 9 for the closed-primary-nozzle configurations. The addition of the outer shroud to the open primary-nozzle configurations generally reduced the thrust ratio at the low secondary and tertiary flow system pressure ratios. At high secondary and tertiary pressure ratios, the addition of the outer shrouds increased the thrust ratio at some conditions. For the closed-nozzle configurations (fig. 9), no consistent thrust trends were evident.

A change from the closed-primary-nozzle configurations (fig. 9) to the open-nozzle configurations (fig. 8) corresponding to a change from nonafterburning to afterburning configurations did not result in any general significant changes in thrust. However, at the lower primary pressure ratios, opening of the primary nozzle reduced the thrust losses of the ejectors with larger outer-shroud spacing ratio as a result of decreasing the overexpansion of the primary jet in the ejector shrouds (compare configuration CC with C and DD with D). Gross thrust losses as great as 12 percent were indicated at the low primary pressure ratios with the configurations investigated, and gross thrust gains as large as 12 percent are indicated at a primary pressure ratio of 9.4. The gross thrust gains are a result of the combination of increased mass flow and the action of the ejector simulating that of a convergent-divergent nozzle at the very high primary pressure ratios.

Application of Data

The actual performance of an ejector in a given airplane installation will depend upon the match point of the flow system (air source, inlet-diffuser pressure recovery, and cooling-system ducting losses) and on ejector characteristics as a pump. A correction to the air-flow-ratio requirements must be made for the ratio of cooling-air temperature to engine gas temperature as described in reference 2. However, this correction will not be exact and at high temperature ratios considerable error may result as shown in reference 4. It is believed, however, that the comparisons shown are somewhat more pessimistic than would have been obtained if the first requisite of model theory had been preserved, namely, that the models be exact scale models of the ejectors used.

The effect of high temperature ratios on performance has not yet been completely defined. For ejectors with the secondary air flow blocked off, an increase in jet-air temperature to 400° F has been shown to reduce the ejector thrust a small amount (reference 5). For much higher air temperatures, the thrust loss would tend to be greater but with a secondary air flow there is a cushioning effect on the expansion of the primary jet, which counteracts the flow characteristic tending to reduce thrust. Until additional high-temperature data are available, it is necessary to assume that the thrust performance to be expected from full-scale double-shroud cooling-air ejectors is reasonably well indicated by the results of the model ejector investigations.

Because of the restrictions to secondary flow, the ejector data presented herein are applicable only to ejectors having similar configurations. If the secondary pressure had been measured at the plane of the primary jet nozzle exit, the pressure loss due to the restrictions would have been included in the ejector performance parameters and would have made the data more general. The trends indicated by the data may be used, however, as a guide for double-shroud-ejector design.

CONCLUDING REMARKS

Double-shroud-ejector configurations intended to supply separate tail-pipe and fuselage cooling-air systems have been briefly investigated. Ten configurations varying in both inner and outer shroud diameter ratios and spacing ratios were examined over a wide range of operating conditions. The data showed that a double-shroud ejector can be designed to give a low weight flow through the outer shroud if the outer shroud is so designed that there will be only a small difference between the diameter and spacing ratios of the inner and outer shrouds. Also, the addition of an outer shroud will not effectively alter the

thrust of an ejector if the difference in diameter and spacing ratios of the inner and outer shrouds is small, particularly at the higher primary pressure ratios.

The use of the clamshell-type variable-area primary nozzle appeared to have little effect on performance as a result of its nonplanar and noncircular exit. However, the movable-clamshell restriction to flow in the cooling-air passage created a large pressure drop not accounted for by the specification of the usual configuration parameters (diameter and spacing ratios, and the cone angle of primary nozzle and shrouds). The large pressure loss in turn appreciably reduced the performance of the ejector as a pump.

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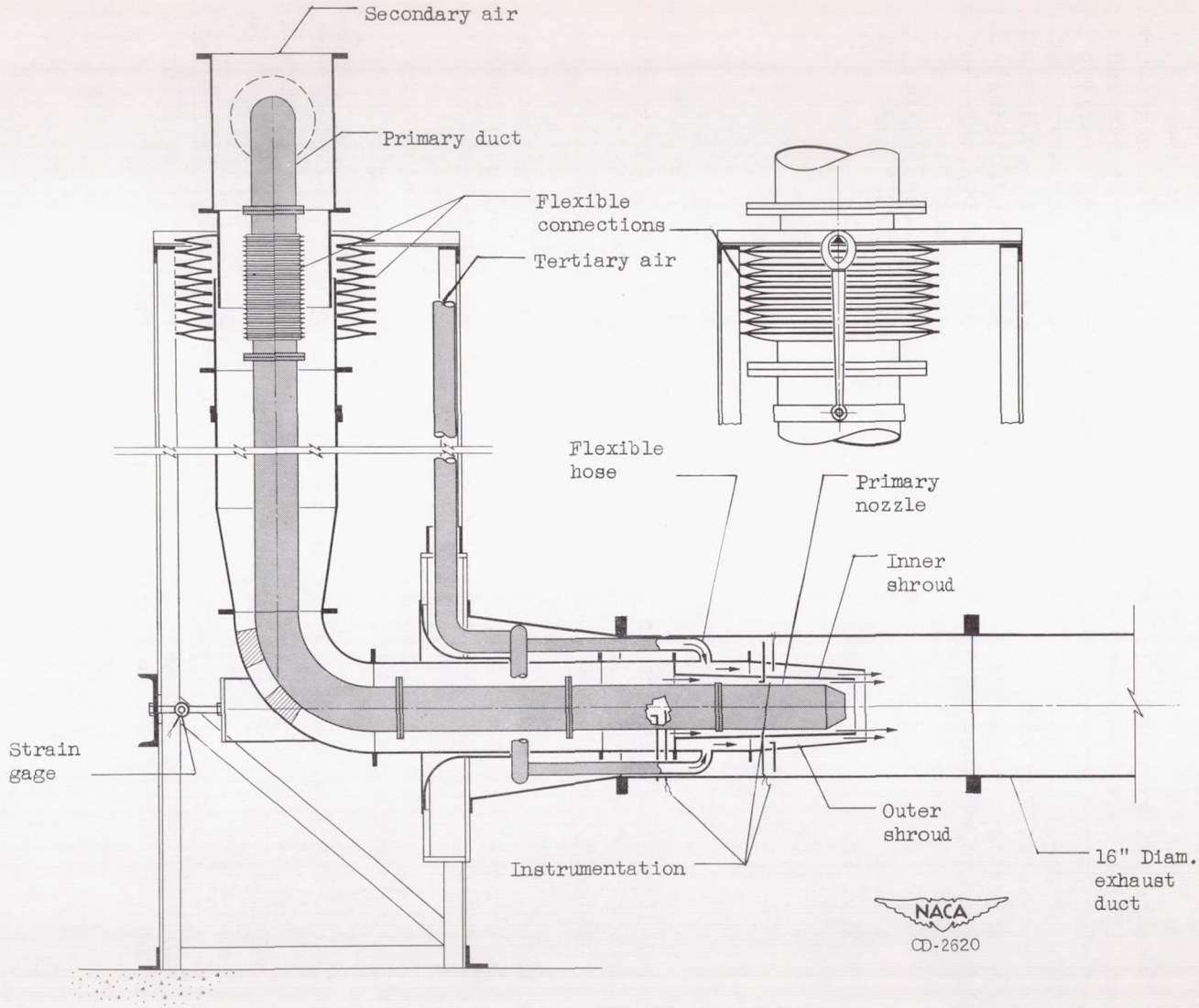
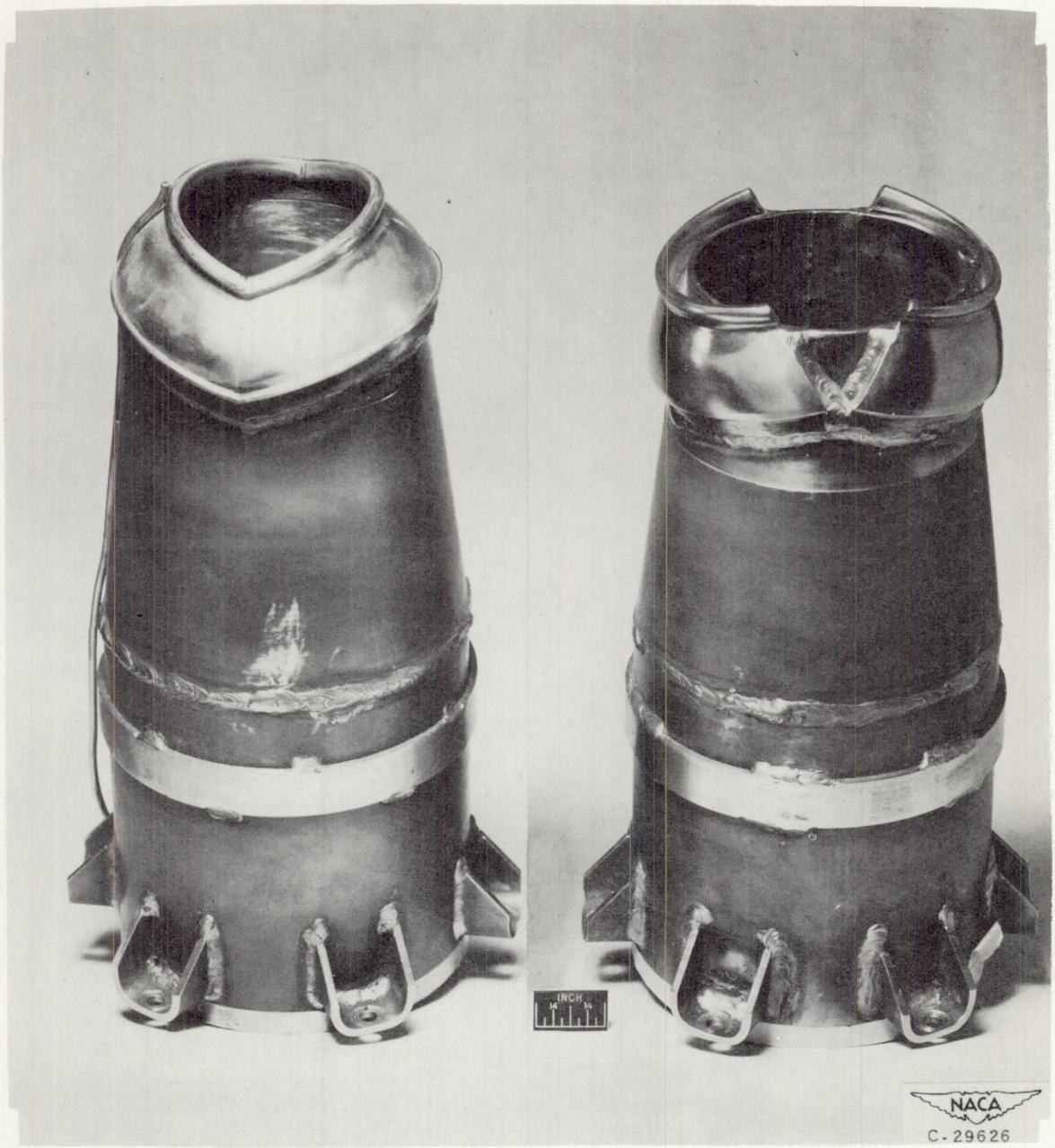
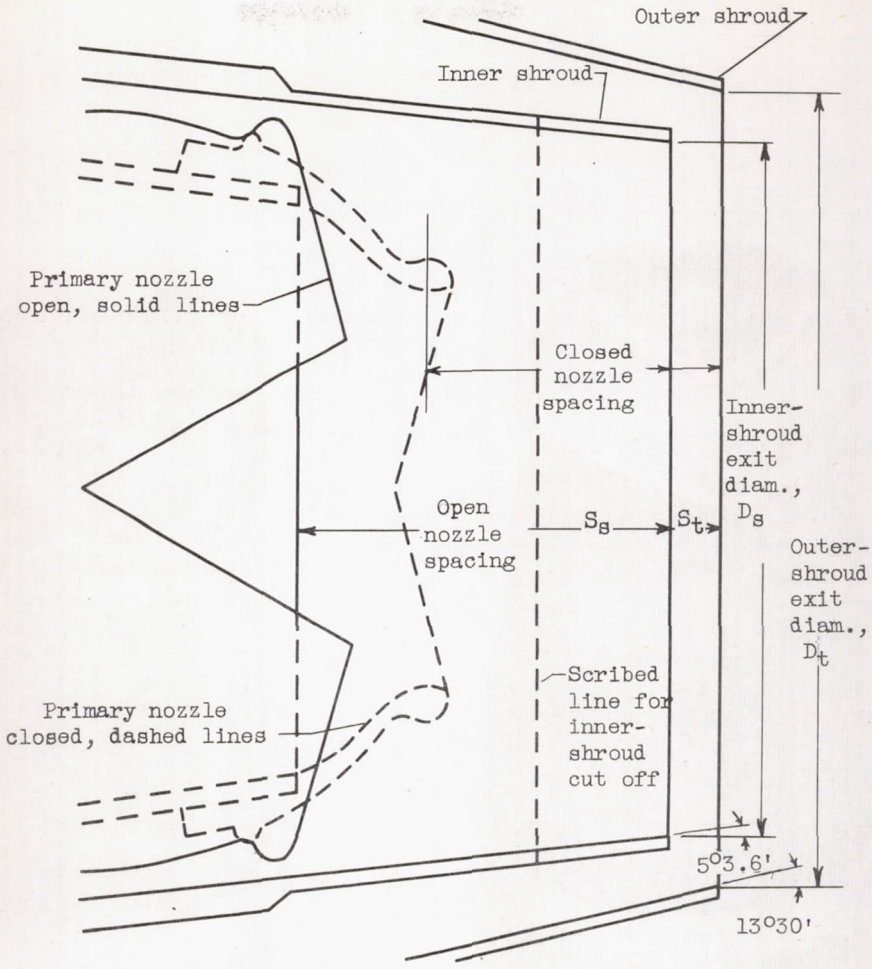


Figure 1. - Ejector research facility.



(a) Closed nozzle (b) Open nozzle

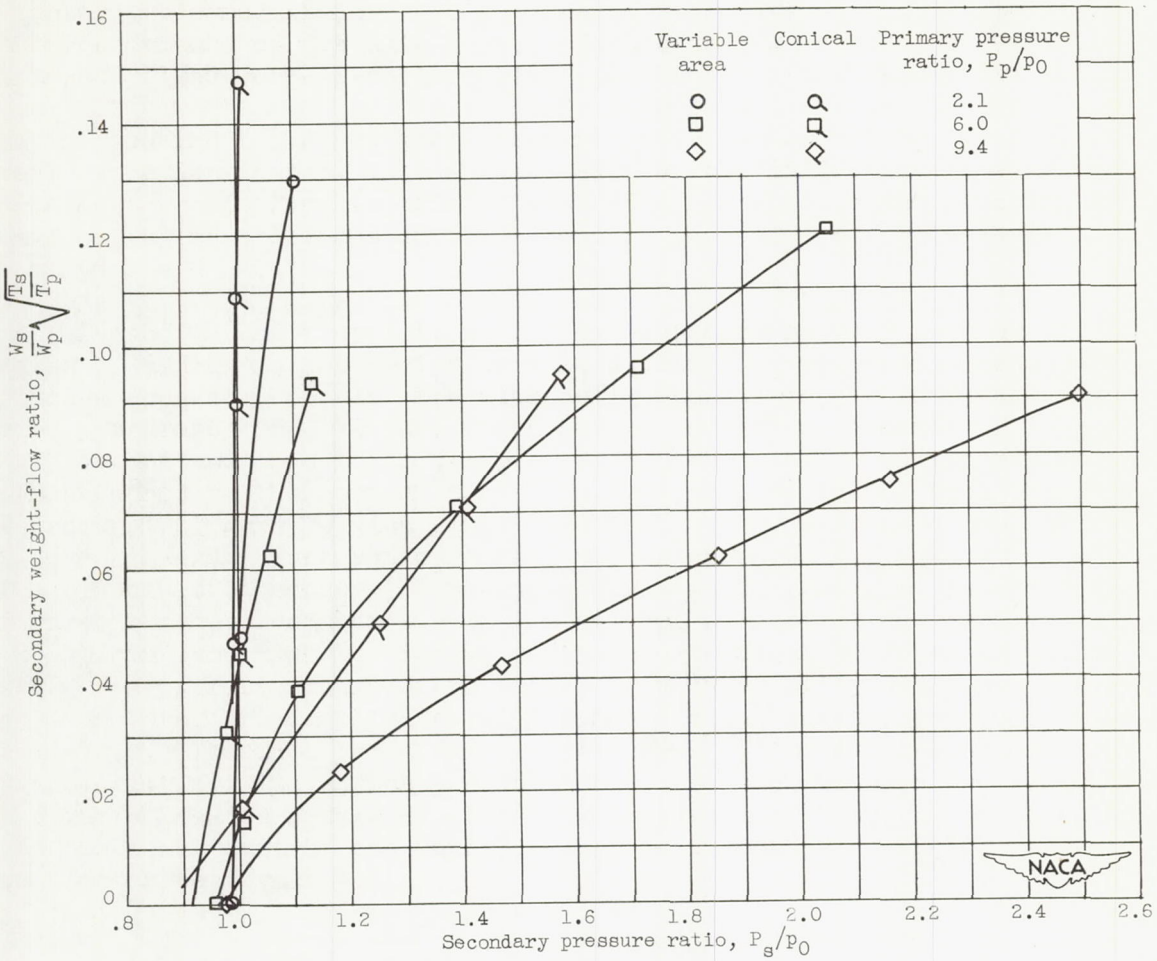
Figure 2. - Nozzles used to simulate variable-area nozzle in ejector models.



Configuration	Nozzle position	D_s/D_p	S_s/D_p	D_t/D_p	S_t/D_p	D_t/D_s	S_t/D_s
A	Open	1.23	0.61	1.39	0.73	1.13	0.094
B	Open	1.23	.61	1.39	.82	1.13	.167
C	Open	1.23	.61	1.39	.97	1.13	.288
D	Open	1.23	.61	1.29	.66	1.05	.042
E	Open	1.23	.61	----	----	----	-----
F	Open	1.27	.42	1.39	.77	1.10	.268
AA*	Closed	1.55	.55	1.76	.70	1.13	.094
BB	Closed	1.55	.55	1.76	.81	1.13	.167
CC	Closed	1.55	.55	1.76	.99	1.13	.288
DD	Closed	1.55	.55	1.63	.62	1.05	.042
EE	Closed	1.55	.55	----	----	----	-----
FF	Closed	1.6	.26	1.76	.69	1.10	.268

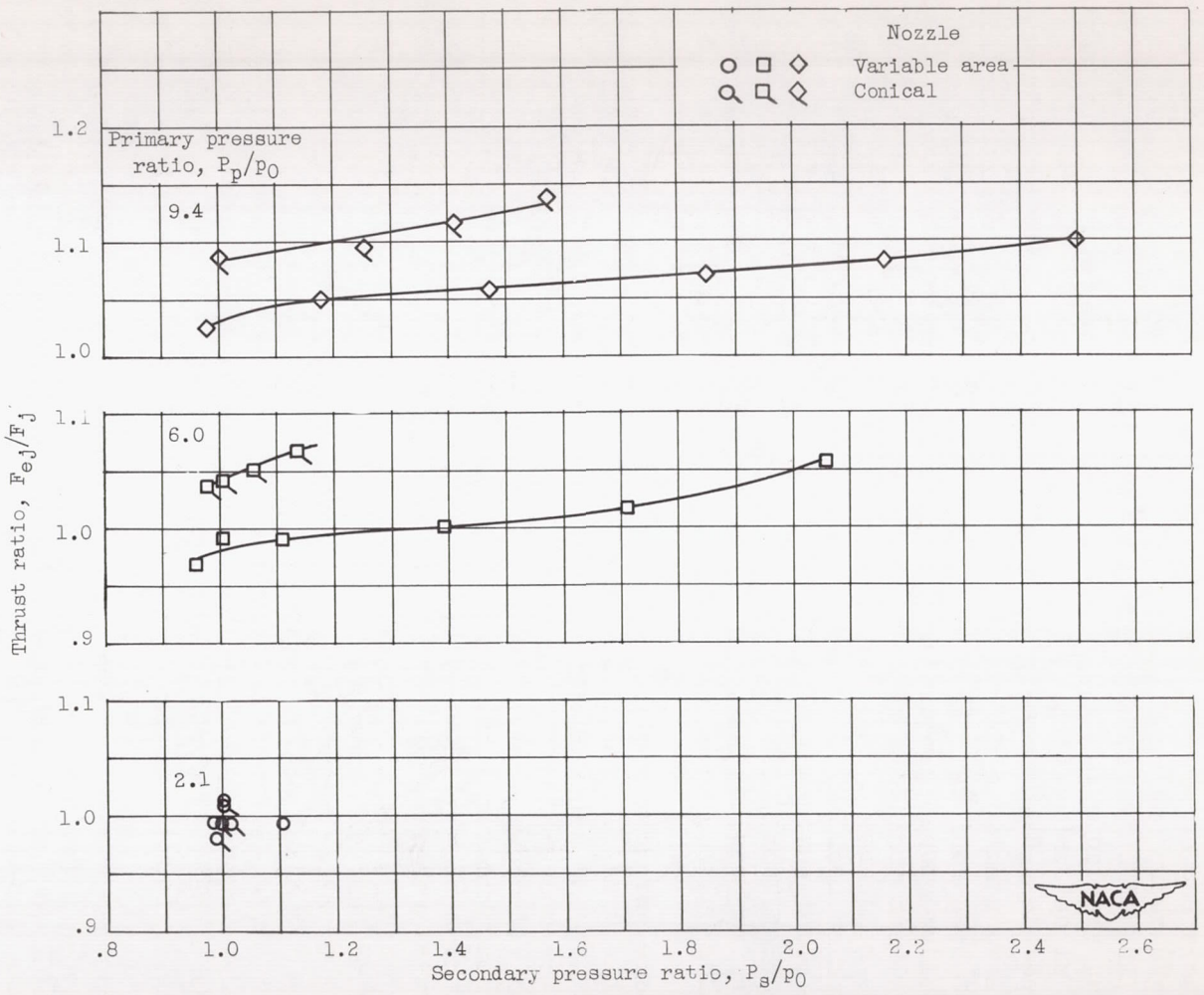
*Configuration AA same as A and BB same as B, etc., except primary variable-area nozzle closed.

Figure 3. - Ejector notation and description of ejector models.



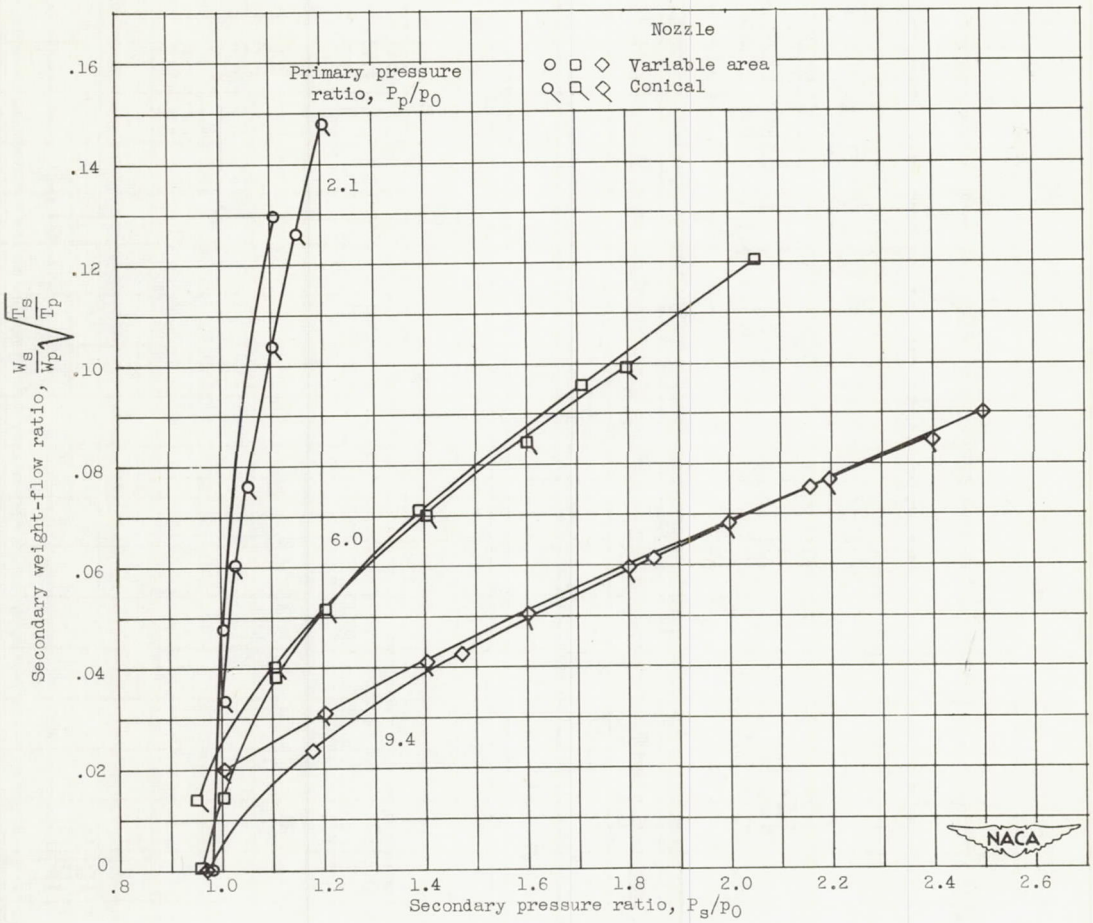
(a) Weight-flow ratio.

Figure 4. - Comparison of performance of ejector having a variable-area primary nozzle with ejector having a fixed conical nozzle. Inner-shroud diameter ratio, D_s/D_p, 1.55; inner-shroud spacing ratio, S_s/D_p, 0.55.



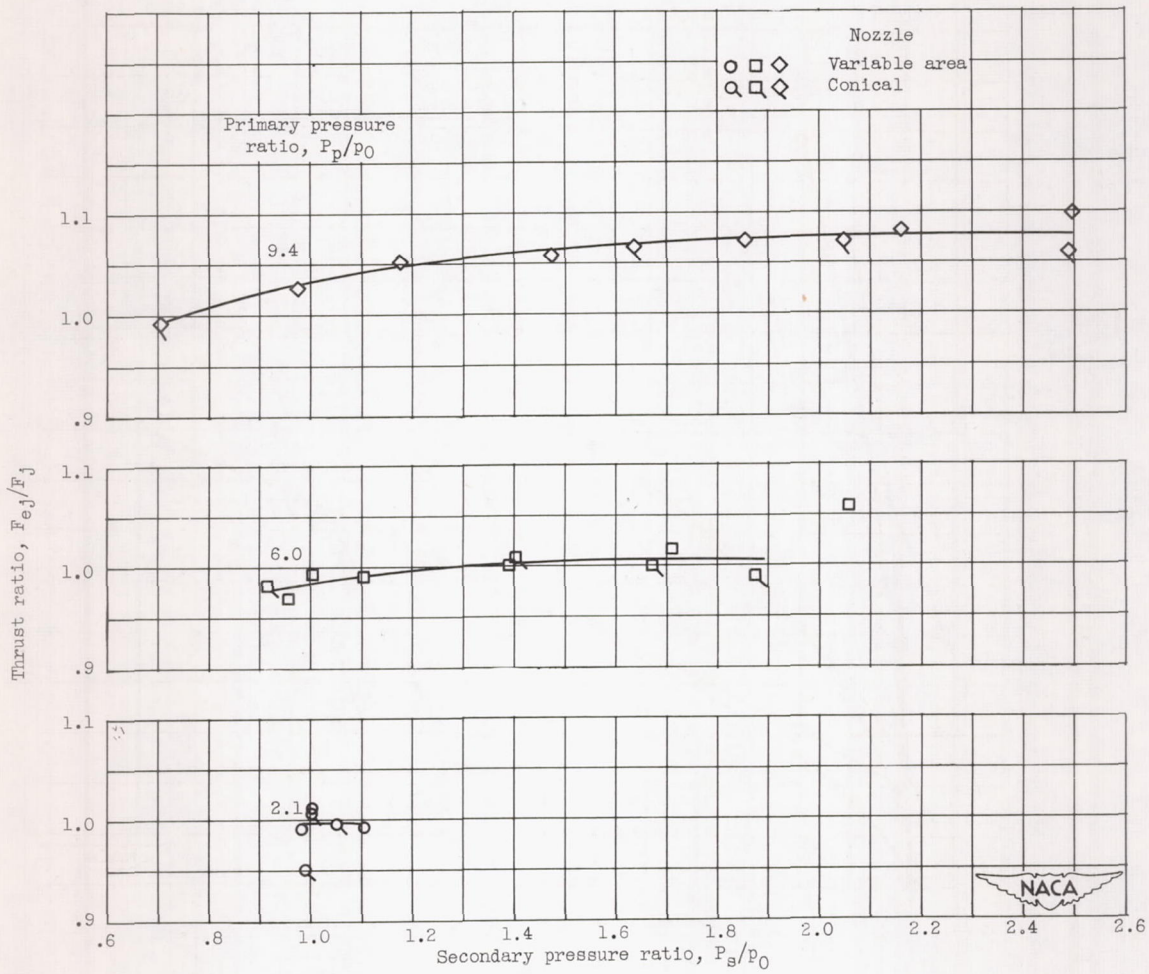
(b) Thrust ratio.

Figure 4. - Concluded. Comparison of performance of ejector having a variable-area primary nozzle with ejector having a fixed conical nozzle. Inner-shroud diameter ratio, D_s/D_p, 1.55; inner-shroud spacing ratio, S_s/D_p, 0.55.



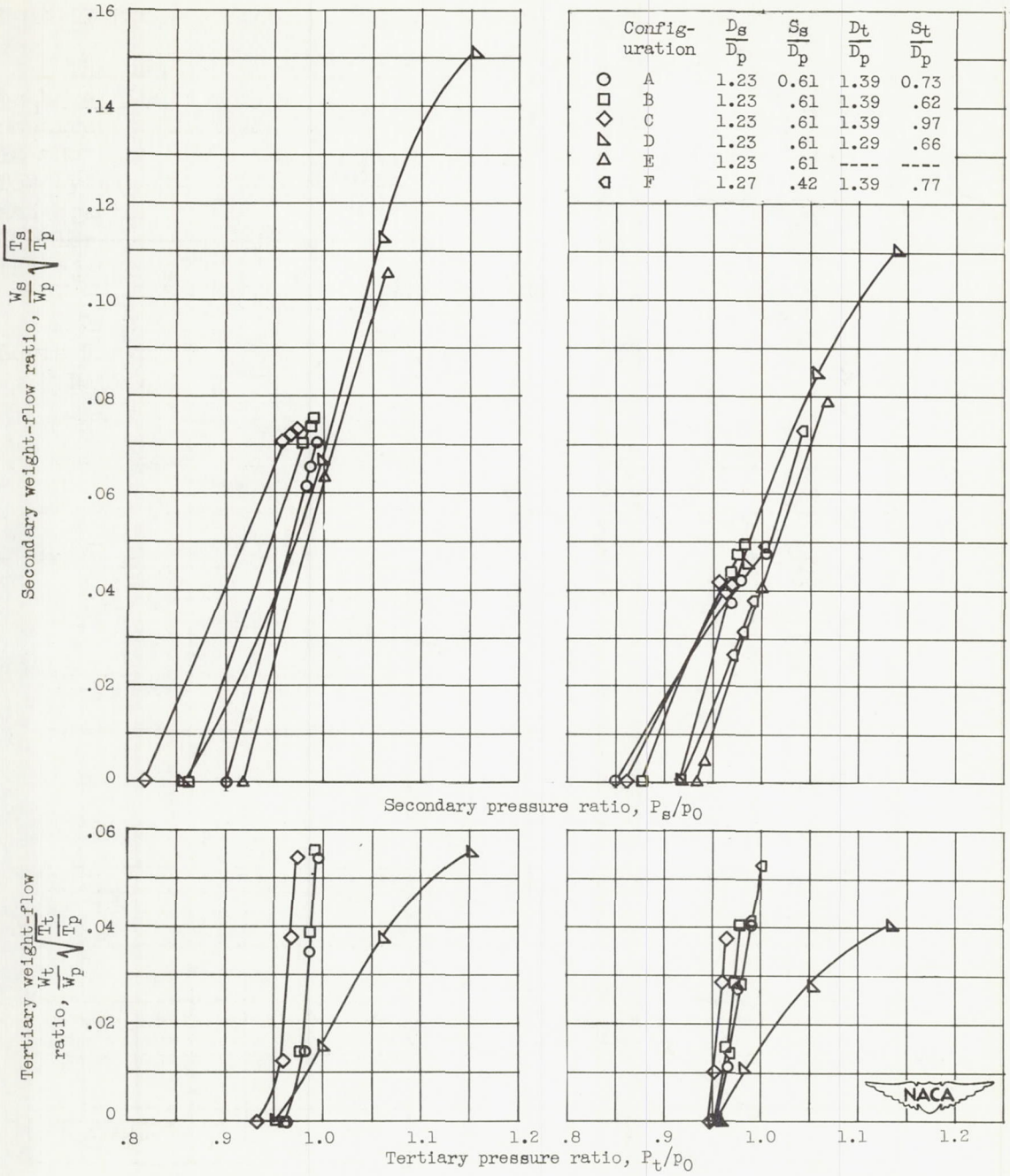
(a) Weight-flow ratio.

Figure 5. - Comparison of performance of ejector having a variable-area primary nozzle with ejector having a fixed conical nozzle and secondary-flow passage blocked to provide minimum secondary-flow passage equal to that of the variable-area nozzle flow passage. Inner-shroud diameter ratio, D_s/D_p, 1.55; inner-shroud spacing ratio, S_s/D_p, 0.55.



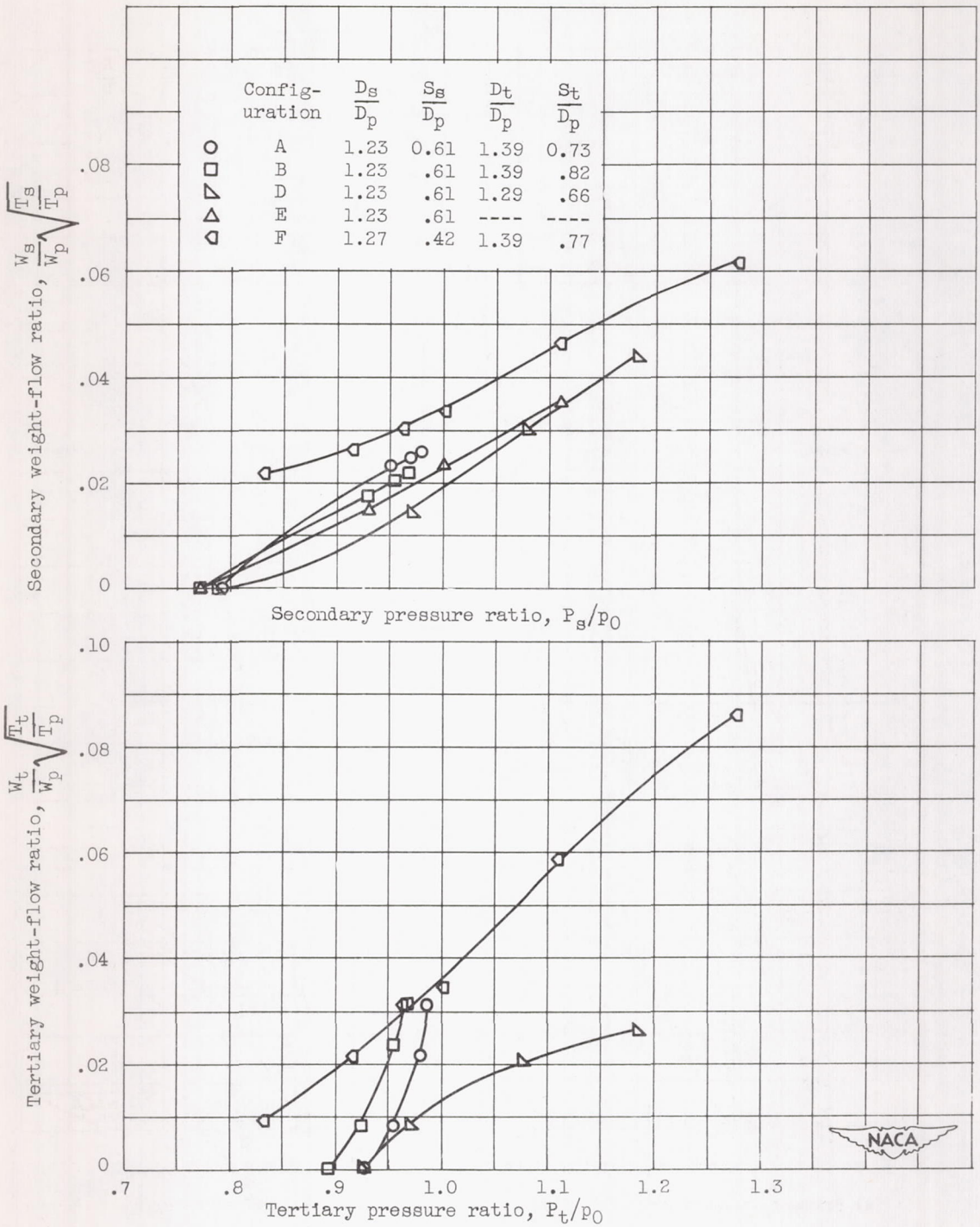
(b) Thrust ratio.

Figure 5. - Concluded. Comparison of performance of ejector having a variable-area primary nozzle with ejector having a fixed conical nozzle and secondary-flow passage blocked to provide minimum secondary-flow passage equal to that of the variable-area nozzle flow passage. Inner-shroud diameter ratio, D_s/D_p, 1.55; inner-shroud spacing ratio, S_s/D_p, 0.55.



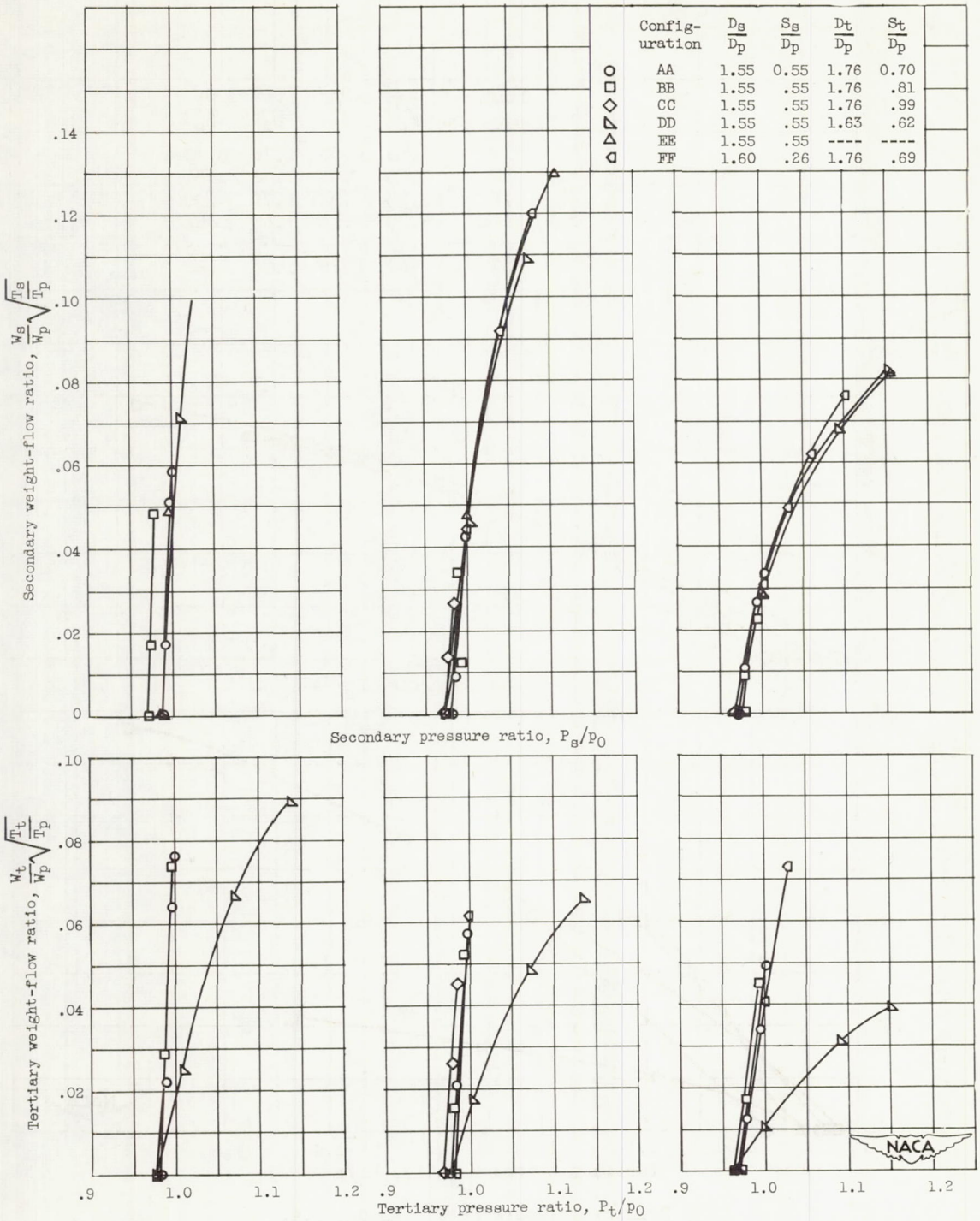
(a) Primary pressure ratio P_p/p_0, 1.6. (b) Primary pressure ratio P_p/p_0, 2.1.

Figure 6. - Double-shroud ejector pumping characteristics with primary nozzle in open position.



(c) Primary pressure ratio P_p/p_0, 3.7.

Figure 6. - Concluded. Double-shroud ejector pumping characteristics with primary nozzle in open position.

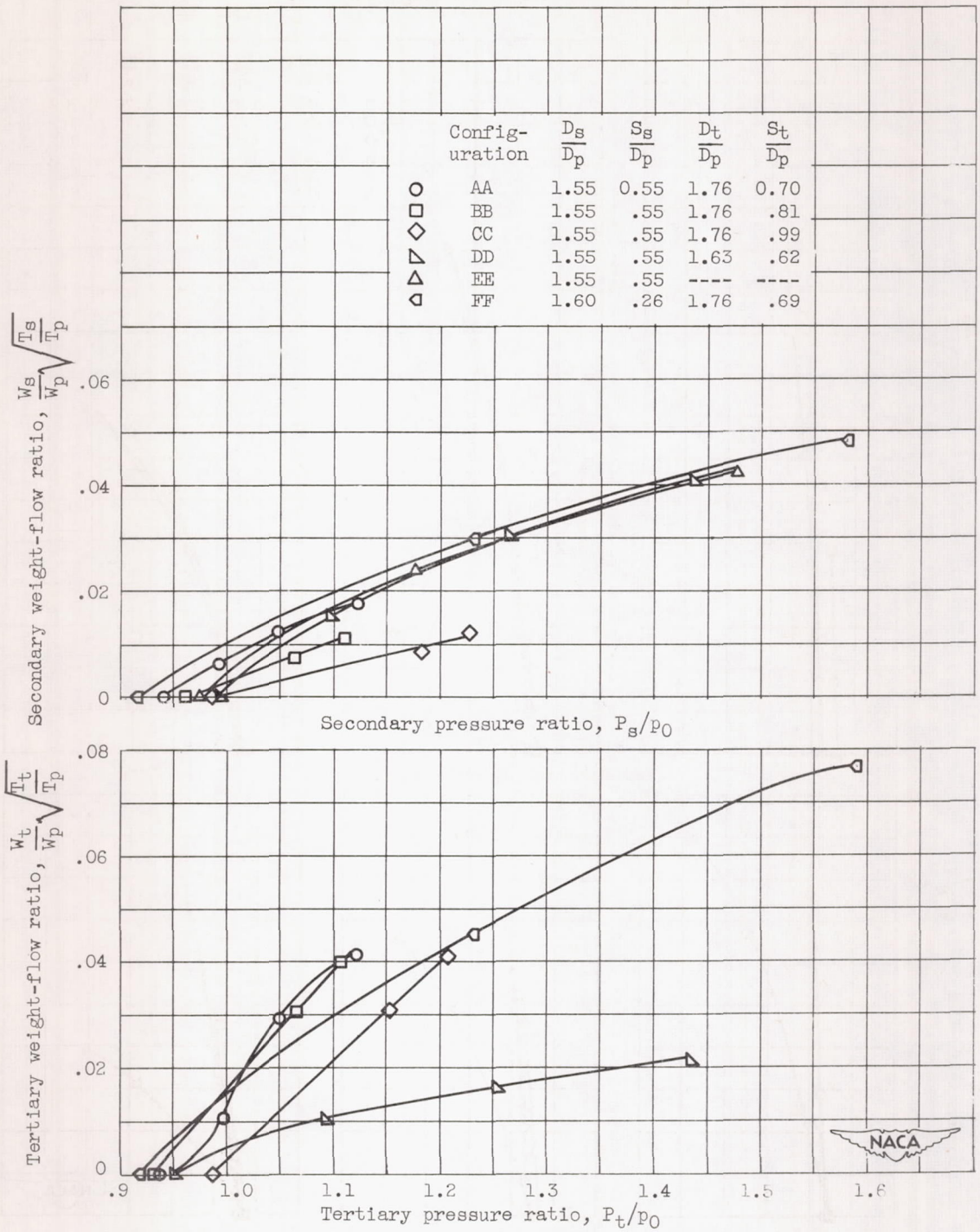


(a) Primary pressure ratio, P_p/p_0, 1.6.

(b) Primary pressure ratio, P_p/p_0, 2.1.

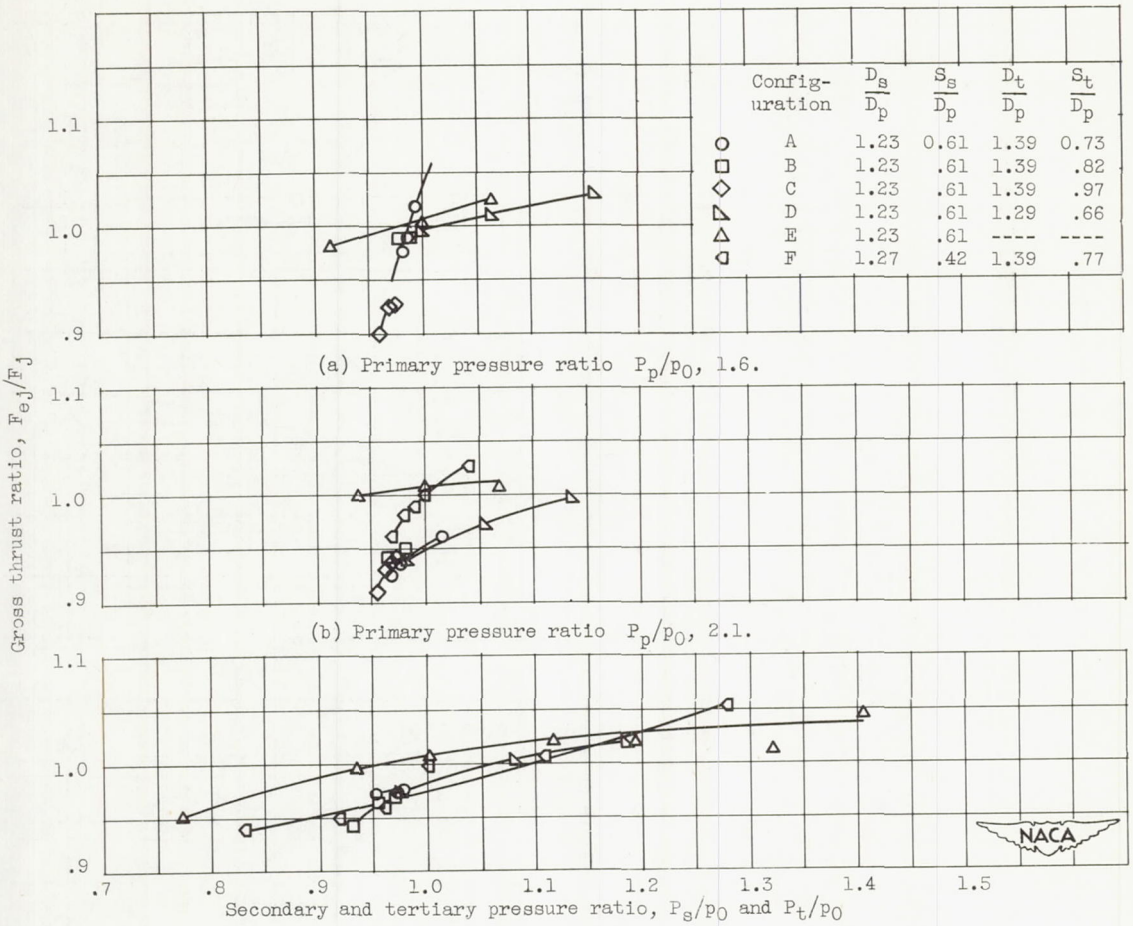
(c) Primary pressure ratio, P_p/p_0, 3.7.

Figure 7. - Double-shroud ejector pumping characteristics with primary nozzle in closed position.



(d) Primary pressure ratio P_p/p_0, 9.4.

Figure 7. - Concluded. Double-shroud ejector pumping characteristics with primary nozzle in closed position.



(a) Primary pressure ratio P_p/p_0, 1.6.

(b) Primary pressure ratio P_p/p_0, 2.1.

(c) Primary pressure ratio P_p/p_0, 3.7.

Figure 8. - Ejector thrust characteristics with primary nozzle in open position.

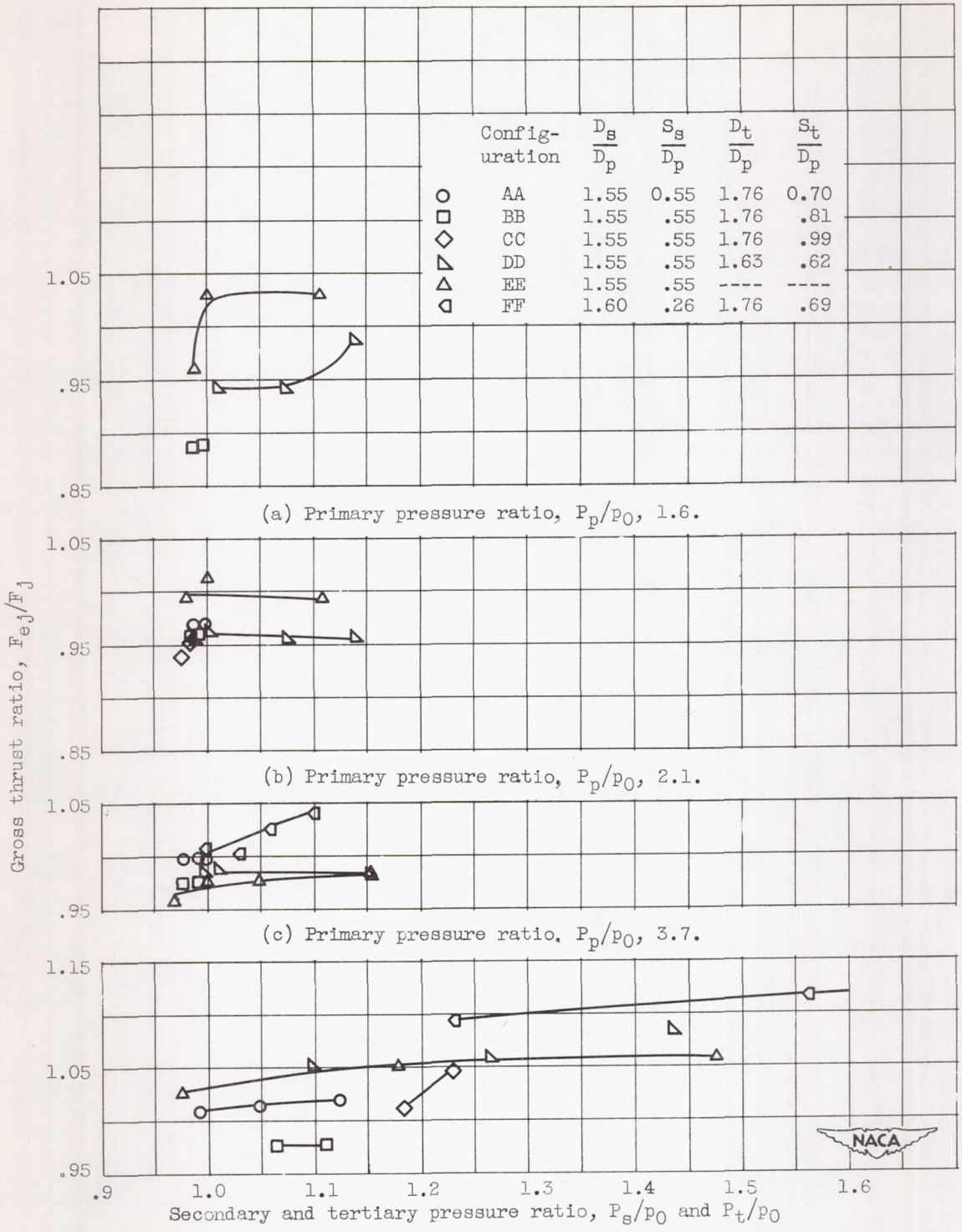


Figure 9. - Ejector thrust characteristics with primary nozzle in closed position.